Journal of Hydrology 522 (2015) 684–696

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Historical reconstruction and 2050 projections of water demand under anthropogenic and climate changes in two contrasted Mediterranean catchments

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ARTICLE INFO

Article history:
Received 9 October 2014
Received in revised form 9 January 2015
Accepted 12 January 2015
Available online 20 January 2015
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Water demand
Anthropogenic changes
Climate change impacts
River Ebro
River Herault

SUMMARY

This paper presents an integrative conceptual framework developed to simulate the spatial and temporal dynamics of water demand caused by human influences and climate change, at the river basin management scale. The past dynamics of urban, agricultural, and industrial components of water demand were simulated at a 10-day time step for the period between 1970 and 2009. The same model was used to forecast water demand at the 2050 horizon under water use scenarios based on local projections, trends observed in the past, and climate scenarios. Climate prediction uncertainties were taken into account using a wide range of climate scenarios downscaled from 9 IPCC-AR5 GCMs under RCP8.5. To test how widely and easily our approach can be applied, we tested it in two river basins facing different kinds of human pressure and different water management issues: the Herault basin (2500 km^2) in France and the Ebro basin (85,000 km^2) in Spain. Results showed that water demand has increased significantly in the last 40 years in both the Herault basin (+29%) and the Ebro basin (+57%), and revealed spatially heterogeneous variations in water demand. Identifying the main drivers of water demand and their past dynamics enabled us to build water use trend scenarios at the 2050 horizon. Simulations of water demand under anthropogenic and climate trends in 2050 revealed a significant increase in total water demand in both basins (Herault +38% to +50%, Ebro +35% to +58%). These projections show that changes in the pressure of human activities will influence variations in water demand more than climate change. The broader aim of this research is to assess the balance between water demand and supply through a comprehensive modeling framework to evaluate the sustainability of water uses in a changing environment.

1. Introduction

1.1. On the lack of knowledge regarding water demand in the Mediterranean region

The Mediterranean basin is characterized by limited water resources and increasing human activities, resulting from a 70% increase in population since 1970 (United Nations, 2013). Further substantial increases in both the population and seasonal tourism are forecasted in many Mediterranean countries (Burak et al., 2004; Gober, 2010), particularly in coastal regions. These changes will most likely result in an increase in agricultural production to meet the needs of the growing population, in turn leading to an increase in water demand and to significant changes in water use patterns. In regions where water stress is already high, the combined impact of increasing needs and decreasing water availability due to climate change could lead to severe water shortages and major water use conflicts (Milano et al., 2013a). Although dedicated studies on the southern rim (e.g. Hoekstra and Chapagain, 2007) underlined the very probable intensification of the water crisis, the question still remains whether future water demand on the northern rim can be satisfied even if population growth is lower.

In recent decades, national water management strategies in the Mediterranean region that favor supply-side policies have mostly led to overexploitation of groundwater and river systems, and to environmental degradation due to the proliferation of dams and canals. Recent studies (Collet et al., 2013; Milano et al., 2013b) confirmed that some basins on the northern rim of the Mediterranean already faced water scarcity periods of varying intensity in the recent past. This has led local policymakers, through the Mediter-

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http://dx.doi.org/10.1016/j.jhydrol.2015.01.029
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ranean Strategy for Sustainable Development (Plan Bleu, 2005), to suggest to "reorient water policies to integrate water demand management in agriculture and other sectorial policies; and encourage demand-side approaches".

At the basin scale, these new strategic guidelines have led policy-makers and local managers to consider implementing demand-side approaches throughout their territory. However, knowledge of water demand is limited, and its assessment can be complex. Although local stakeholders on the northern rim of the Mediterranean often have basic knowledge of current water withdrawals and their distribution between different uses, there is a serious lack of information on the dynamics of different water uses in space and over time. To tackle these issues, the scientific community has begun to incorporate water uses in water resources management studies (e.g. Charlton and Arnell, 2011; Collet et al., 2013; Griffin et al., 2013), combining physical and human features and causing interdisciplinary problems.

As water management increasingly turns to demand-side approaches, reliable methods of assessing water demand are indispensable. Such methods should be able to assess the dynamics and determine the main drivers of each type of water demand, and be able to project future water uses. In parallel, global scale studies have highlighted the potentially significant impact of climate change on future water demand (Alcamo et al., 2003; Vörösmarty, 2000) and raise the question of its effects at the local scale or at the management unit scale. The forecasting dimension of water demand assessments at a local scale is an integral part of water management strategies to ensure the sustainability of water supply (e.g. Reynard et al., 2014).

1.2. Scientific and technical challenges in the assessment of water demand

A review of the literature revealed that water demand is most often tackled in studies that compare water supply and demand in terms of water stress and/or the vulnerability of territories to climate change (e.g. de Graaf et al., 2004; Beck and Bernauer, 2011; Collet et al., 2014; Dawadi and Ahmad, 2013; Milano et al., 2013b; Hejazi et al., 2014). Three main issues were identified in these studies: (i) water demand is not always considered as a whole i.e., not all its components (agricultural, urban, industrial, energy) are accounted for; (ii) spatialization of data is not always consistent with the goals of connection with water supply assessment; and (iii) the reduced time depths and large time steps usually used, do not accurately account for the temporal variability of the drivers of water demand.

Although the assessment of water demand requires interdisciplinary approaches, often only one of its components is analyzed. For example, in Breyer et al. (2012), water use patterns only focused on residential water requirements. In the same way, Ruijs et al. (2008) only considered the effect of water pricing policies on urban water demand. Numerous studies focused on agricultural water needs based on irrigation water (e.g. Rosenzweig et al., 2004; Thomas, 2008; Schaldach et al., 2012; Mullen et al., 2009; Minacapilli et al., 2008; Wu and Chen, 2013). This is probably because in many regions irrigation is the main water use and the development of irrigated areas is often considered as a strategic way to maintain agricultural activity. However, prioritizing water uses requires taking all water demands, even those that consume the least water (including water for the habitats for fauna or immaterial uses such as the landscape use of waters), into account.

As underlined by Boithias et al. (2014), the assessment of water demand needs to be spatially distributed, as the results can differ depending on the spatial scale considered (Syrbe and Walz, 2012). Hejazi et al. (2014) also point to the need to spatially downscale water demand to be consistent with representations of water availability. To be compared with available water resources, water demand needs to be represented on a relevant scale that is compatible with the main hydrological features (storage dams, river catchments). The spatial aggregation of water demand into demand nodes also needs to account for heterogeneities in water uses throughout the territory (water withdrawals and transfers, main irrigation systems). In addition, the availability and the quality of data strongly influence the definition of water demand nodes. Consequently, defining demand nodes consistent with hydrological constraints is becoming a key issue for water demand studies.

The choice of the time depth and time step influences the results of water demand assessments. Multi-decadal time periods should be used to characterize historical variations in water uses, trends, and discontinuities in human activities. Highlighting and understanding these dynamics along with breaks that occurred in the past makes it possible to identify the main drivers of changes in water demand and, consequently, enables the design of more realistic future water use scenarios. Previous studies (Collet et al., 2013; Milano et al., 2013b) identified trends and breaks in water demand in recent decades in northern Mediterranean regions. They showed that human-induced changes such as population growth, expansion of irrigated areas or improvement of network efficiency can have a significant impact on water demand, which cannot be identified if the focus is limited to current water uses. Time depth also makes it possible to capture the influence of climatic variability on irrigation needs, for example. In addition, water demand assessments can be strongly influenced by the time step chosen for the analysis. The choice of a time step is generally closely linked to the spatial scale and to the time depth of the study: the larger the spatial scale and/or time depth, the larger the time step. While global scale studies rely on yearly analysis (e.g. Alcamo et al., 2003; Döll, 2002; Vörösmarty, 2000), a monthly time step is generally used at the basin scale (e.g. Koch and Vögele, 2009; López-Moreno et al., 2011; Salvador et al., 2011). This finer time step is appropriate when studying urban and agricultural demands, which are seasonally driven by tourism and crop phenology, respectively. Notably, irrigation water requirements generally decrease with an increase in the time interval, as pointed out by Green (2008). In addition, a narrow time step makes it possible to take the water recharge of the soil buffer reservoir into account more accurately in an irrigation water model. However, a monthly time step does not account for infra-monthly rainfall variability that can be very high in the Mediterranean region. In a theoretical assessment model of irrigation water requirements, considering the soil and its buffering effect, the infra-monthly distribution of rainfall and, to a lesser extent, the temperature, can have a significant impact on water requirements.

1.3. An integrative approach to reach these goals

Water management stakes on the northern rim of the Mediterranean and the shortcomings identified in the scientific literature underline the need to quantify water demand by accounting for human and climatic drivers at appropriate spatial and temporal scales. The purpose of this paper is thus to present an integrative conceptual framework to accurately simulate water demand under anthropogenic and climate changes. First, we assess each component of water demand and its spatial and temporal dynamics over a long past time period. Second, we use the same framework to forecast water demand at the 2050 horizon under water use scenarios based on local projections and following trends observed in the past, and climate scenarios built according to recent runs of IPCC climate models. To test how widely and easily our approach is applicable, we decided to tackle these issues by analyzing two different territories facing strong but diverse anthropogenic pressures and different water management issues.